Technological Forecasting & Social Change 126 (2018) 194–206

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

Technology roadmapping: A methodological proposition to refine Delphi results

Luiz A. Bloem da Silveira Junior[a,*], Eduardo Vasconcellos[a], Liliana Vasconcellos Guedes[a], Luis Fernando A. Guedes[b], Renato Machado Costa[a]

[a] University of São Paulo, Department of Business Administration at FEA/USP, Av. Prof. Luciano Gualberto, 908, 05508-900 Sao Paulo, Brazil
[b] FIA - Administration Institute Foundation, R. José Alves Cunha Lima, 172, 05360-050 Sao Paulo, Brazil

ARTICLE INFO

Keywords:
Technology forecasting
Technology roadmap
Delphi technique
Action research
Decision matrix
Morphological analysis

ABSTRACT

This study outlines a methodology to refine Delphi results as part of the process to design a technology roadmap. The objectives of this paper are: (a) present a methodology to design a TRM using Delphi associated with other techniques (morphological analysis, decision matrix, interviews, and prioritization analysis), and (b) demonstrate and discuss the application of proposed TRM methodology to define alternative materials aiming to reduce the weight of structural shock absorbers. The field research consisted of a case study approach in the Brazilian subsidiary of an Italian auto parts MNC combined with action research methodology. The main contributions of this paper are: a) The proposition of a methodology to refine Delphi results as part of the process to design a technology roadmap (TRM), including a decision matrix, interviews with external experts, and a prioritization analysis and b) The action research provided good quality results as well as an opportunity to test the methodology in a company environment during eight months; this is not common to find in the literature.

1. Introduction

Technology planning is a key tool to increase competitiveness. Clark and Wheelwright (1993:91) state that the objective of technology strategy is "to guide the company in the acquisition, development, and application of technology in order to obtain competitive advantage" and it must fit into company's strategic objectives. It is not enough for the company to have an R & D department with all the required equipment and qualified researchers; it is necessary that operational excellence to be supported by strategic processes in order to allow the company to identify if technology innovation opportunities are really feasible and compatible with market demands.

Technology forecasting (TF) techniques is key to technology management as it can anticipate technology trends in, contributing to decision-making, resource allocation, risk analysis, and the definition of technologies and competencies to be developed. The role of TF can be classified as four components (Yoon and Park, 2007). Initially, TF innovation enables the manager to view the most likely direction that technology will take and develop technological plans to prepare for this new possible reality. Second, it explores new technologies and the time required to develop them internally. Third, it identifies enablers and restrictors for the development of technologies, and ultimately aids interaction between researchers, fostering collaboration in the development of new technologies.

The literature and managerial practices have identified a number of techniques for prospecting technologies. Among them are environmental scanning, Delphi, morphological analysis, roadmapping, bibliometric analysis, and the theory of inventive problem solving (TRIZ). Several of them are supported by algorithms (including techniques such as artificial neural networks), and it is not rare that many are used simultaneously when dealing with a complex subject (Yoon and Park, 2007).

Technology roadmap (TRM) is one of the most important methods for prospecting technology (Coates et al., 2001). According to Phaal and Palmer (2010:64), "Roadmaps are representations (usually visual) of strategy, which can take many forms, developed to summarize outputs from a roadmapping process for reporting and dissemination purposes." The roadmapping integrates R & D programs, market requirements and training objectives (Kostoff and Schaller, 2001). The method helps to develop consensus among decision makers to formulate short- and long-term technological strategies, both of them based on the interaction between products and technologies over time (Groenveld, 2007). Although the greatest advantage of TRM is to be an effective vehicle for decision making in a multidisciplinary and multifunctional approach this may also be its greatest weakness, since the quality of the process depends on the knowledge of the people who create the maps.

* Corresponding author.
E-mail addresses: luizbloem@usp.br (L.A. Bloem da Silveira Junior), lilianav@usp.br (L. Vasconcellos Guedes), rmcosta@usp.br (R.M. Costa).

http://dx.doi.org/10.1016/j.techfore.2017.08.011
Received 17 November 2016; Received in revised form 4 July 2017; Accepted 25 August 2017
Available online 06 September 2017

There are several techniques to gather information for the elaboration of a TRM, such as quantitative analyzes of patent bank data (Lee et al., 2008), reverse engineering with benchmark analysis (Lee et al., 2007), external database analyses (Jin et al., 2015), morphological analysis (Yoon et al., 2007). Since TRM development demands support from field experts in the areas of analysis, the use of the Delphi methodology stands out in relation to the other TF techniques. Delphi method aims to obtain a reliable consensus of a group of experts (Lee et al., 2013;Mitchell, 1992 ; Yoon and Park, 2007). Thus, the combined use of TRM with other prospecting techniques such as the Delphi method and morphological analysis provides better accuracy in the formulation of technological strategies (Mitchell, 1992; Yoon and Park, 2007), in order to build a future vision for the business (Phaal and Probert, 2009). A possible constraint on use of Delphi method in the construction of TRM is that it requires meticulous analysis in the preparation of the survey and a considerable execution time (Kostoff and Schaller, 2001).

Combining other management techniques to TRM can reduce knowledge gaps and improve management decisions. As pointed by Carvalho et al. (2013) there is only a limited research papers addressing hybrid procedures. The tools that can be integrated with TRM and Delphi, include SWOT analysis, five forces of competition, value proposition, competitive features matrix, perceptual map, analytic hierarchy process (AHP), technology development envelope (Fenwick et al., 2009), quality function deployment (QFD) (Lee et al., 2013), portfolio management (Phaal et al., 2006) and technology management tools (Probert et al., 2003).

This research paper outlines a methodology to refine Delphi results as part of the process to design a technology roadmap, including a decision matrix, interviews with external experts, and a prioritization analysis. The objectives of this paper are: (a) present a methodology to design a TRM using Delphi associated with other techniques (morphological analysis, decision matrix, interviews, and prioritization analysis), and (b) demonstrate and discuss the application of proposed TRM methodology to define alternative materials aiming to reduce the weight of structural shock absorbers.

A field research combining a case study with action research was conducted to demonstrate the applicability of the proposed methodology. The case studied was based on the development of a technology roadmap to define alternative materials to reduce the weight of structural shock absorbers at the auto parts company Magneti Marelli COFAP.

The major contribution of this paper is the proposition of methodology that integrates TRM with management techniques in order to improve decision making regarding technology forecast and prioritization. The paper also contributes exemplifying an application of technology roadmap for automotive components and sustainability issues. Phaal and Probert (2009) cite a roadmap study that have been used in more than 900 examples from different sectors such as energy, transport, materials, aerospace, electronics, ICT, manufacturing, construction, health, defense, and pure science, but not including automotive components such as shock absorbers. And Carvalho et al. (2013) identified the application of roadmapping approaches to sustainability issues as a future research perspective, mentioning as an example the need to achieve carbon reduction targets.

The use of action research methodology is also a contribution, since the majority of the studies analyzed by Carvalho et al. (2013) were case studies, and only one used action research. In this research, the action research allowed full access to product and company public data and a deep interaction among researchers and the participants thus providing good quality results as well an opportunity to test the methodology in a company environment. The paper's main author was a former Magneti Marelli innovation manager with extensive practical and theoretical experience with TRMs. He coordinated the implementation of roadmapping as part of a complex and multidimensional innovation project.

The article first presents a theoretical review of technology forecasting tools (objectives and guidelines for the construction of a TRM, morphological analysis, Delphi method, and other tools). Next, the methodological procedures and TRM process are detailed as the company that was the target of the study. This section is followed by the application of the proposed TRM process for reducing shock absorber weigh. Finally, the lessons learned by TRM methods are discussed and conclusions are presented.

2. Theoretical framework

2.1. Technology roadmap objectives and guidelines

Ubiquitous communication technologies, lower transport costs, fewer commercial barriers, customer desires for standardization, and the prominence of transnational corporations have turned markets from the local to the global, raising competition among companies to another level (Porter et al., 1991). Utterback (1994) presents a parallel model for technological innovation based on the interaction between technology users and scientific and technology communities.

According to Porter et al. (1991:9), “in asserting national competitiveness the firm is the center of action because in capitalist economies the firm is almost always the enterprise that must deliver the technology”. The author presents a framework for technology development in the company while considering external (cultural, political, and economic) and internal aspects (scientific and technological resources, R & D funding, patents, and all product development and production factors such as capital, materials, labor, equipment et al.). According to this model, technology management starts with R & D. Product portfolio development must be done in a way to ensure company investments are properly allocated. Moreover, companies in order to prioritize investments must understand technology and market trends through a technology strategy.

From the 1990s, due to the globalization and the increasing competition between nations and companies, we see the resumption of forecasting and technology assessment activities. According to Coates et al. (2001:10), “there was a change of emphasis as to the primary purpose of technology foresight activities: assessing opportunities and threats related to innovations and their implications on the economic performance of organizations”. Traditional product development methods were not abandoned but incorporated within broader frameworks to integrated techniques of competitive technological intelligence, technology and innovation audits, and market analysis with increasing customer involvement. The same authors indicate technological roadmapping and competitive technological intelligence as emerging forms of technology assessment and forecasting, combining the main technological elements in product design and manufacturing with strategies aimed at reaching desired objectives effectively. Porter et al. (2011), in their technology generation model, state that the information collected during forecasts must be classified in an initial map of two different perspectives: the technological components necessary to perform the innovation and the external forces. Business ecosystem and institutional contexts also influence technology and must be addressed.

A study from Coates et al. (2001) identified TRM as a robust forecasting methodology, combining the main technological elements involved in product design and manufacturing with strategies to reach company goals. The main objective of this technique is to develop a map that integrates both technical and commercial perspectives. The TRM presents a holistic business vision, inviting distinct company areas to reflect on how technology can contribute to company competitiveness (Phaal and Probert, 2009). Same authors state that the roadmap elaboration process is as important as the result itself. The roadmap is a living document and as such, it must be updated and disclosed to all internal stakeholders.

TRM was originally developed by Motorola during the 1970s. According to Galvin (1998:803), who was Motorola's CEO in the period of roadmap creation, the roadmap is "an extended vision to the future in a chosen investigation field composed of a collective knowledge and imagination of the brightest change agents in that field". Motorola's concept introduced two types of roadmaps, one related to emerging technologies and other to product technologies. The roadmap for emerging technologies deals with trends in evolving technologies over time, while the product roadmap discuss how the product components (and the product as a whole) can evolve over time. Phaal and Probert (2009) cite the year of 1992 as an important milestone for the diffusion of the TRM, when the first semiconductor roadmap was published. Its use accelerated innovation in this field, consolidating a collective vision for this technology branch and disseminating and popularizing this strategic tool, which went on to be adopted by many organizations of different sectors worldwide.

Important research work on this subject has been done in the UK, from which we highlight the studies of Phaal and Probert (2009), Phaal et al. (2003), Phaal and Palmer (2010), McMillan (2003), Albright and Kappel (2003), Dissel et al. (2009), and Farrukh et al. (2004), among others. Phaal and Probert (2009) present successful cases in areas such as transportation (the Foresight Vehicle program) and emerging technologies (The Measurement and Standards for Emerging Technologies). Vasconcellos et al. (2014) developed a conceptual model to identify technological threats and opportunities using several sources (customers, competitors, suppliers, new entrants, universities, government regulations and policies, as well as infrastructure and the environment). Authors showed that information obtained from these sources was used to improve a new R & D portfolio for generating projects. Phaal et al. (2003) cite research with 2000 manufacturing companies, which indicated that around 10% of the companies (mostly large corporations) were currently applying this technique, and 89% had applied it more than once in the past.

Phaal and Probert (2009) propose a graphic representation of a roadmap with different layers, presenting the visions of "demands" and "offers", balancing the so called *market pull* and *technology push* perspectives. According to the authors, layers of the TRM are built from three perspectives: commercial and strategic (involving market and business analysis), product development and production (encompassing products, services, and systems), and the prospect of access to technology and resources needed to make it viable. Information about these perspectives are raised during the roadmap design (e.g., the market "drivers", strategic vision, and future needs of the company; form, function, and product performance requirements; planned and available technological solutions, technical capabilities, material and necessary skills to enable the desired technologies).

There are several types of roadmaps, but for this research uses "product planning" as per Phaal et al. (2004). This is the most common type of roadmap related to technology aggregation in manufactured products, and usually includes more than one generation of product.

Freeman (1982) states that industrial innovation comprises development of new technologies, design, manufacturing methods, as well as marketing and commercial activities of a new or substantially improved product. Clark and Wheelwright (1993) developed a framework for product development strategy that encompasses four phases: concept development, product planning, product and process engineering, and pilot production/ramp-up.

One must consider sustainability aspects during TRM elaboration as companies must balance economic success with environmental and social concerns, (Stead and Stead, 2000). Porter and Kramer (2006) emphasize that companies must map social impacts in the value chain, and there is no doubt that TRM design must consider this component. Nidumolu et al. (2009) proposed five stages for sustainability attainment: (i) viewing the compliance as an opportunity; (ii) making value chains sustainable; (iii) designing sustainable products and services; (iv) developing new business models; and (v) creating next-practice platforms. These factors can support a TRM design that considers sustainability factors.

2.2. Morphological analysis

Morphological analysis divides a product or process into main components. Morphological analysis, as suggested by Zwicky (1969:15-28), requires the specification of the main functions, elements, or basic parameters of an issue. The author suggests a sequence of five steps for the construction of what he calls the morphological "matrix" or "box", which are: (i) problem formulation; (ii) identification and analysis of all parameters that may be relevant to the solution of the problem at hand; (iii) construction of the morphological "matrix" or "box"; (iv) evaluation of all solutions contained in the morphological matrix against the objectives established for solving the problem; (v) selection of optimized solutions considering feasibility and resources required for achieving them.

Godet (2000) divides the morphological analysis process in two steps using the software Morphol. In the first step, the system under study is deconstructed into subsystems or components (similar to steps 1 and 2 of Zwkicy's approach). Secondly, the morphological space is reduced to a useful subspace through selection criteria (e.g. economic or technical). The author points out that despite being largely used in technology forecasting, morphological analysis is applied to elaborate scenarios.

Yoon and Park (2007) proposed a hybrid approach using morphological analysis with conjoint analysis. This is a technique to determine statistically how participants value different product attributes (feature, function, benefits). This allows product designer to determine the best configuration of a new or improved product or service. The use of this hybrid analysis tool aims to compensate the limitations of morphological (non-quantitative) analysis.

In this research, a morphological matrix was elaborated by experts and the development of alternative technologies was raised for each attribute. Then these alternatives were weighted and prioritized using conjoint and feasibility analysis.

2.3. The Delphi method

Dalkey and associates at the Rand Corporation originally developed the Delphi technique in the 1950s. Initially developed to enhance the use of expert opinion in technological forecasting, the Delphi method has been extensively used to forecast and discuss public policies. Skulmoski et al. (2007:1) point out that "the Delphi method works well especially when the goal is to improve the understanding of problems, opportunities, solutions, or to develop forecasts". Grisham (2009) carried out a literature review on the Delphi method, explaining how this forecasting method as a research tool. His findings showed that Delphi is appropriate for researching complex issues that require expert insights on subject matter, although it does not offer the rigor of clinical testing or quantitative analysis.

Mitchell (1992) emphasizes the importance of applying the method as a strategic tool in new technology industries. The author mentions the advantages when using Delphi as a forecasting tool. Most forecasting methods rely on historical data, thus restricting the use of statistical techniques. Traditional sales forecasting techniques are hampered not only by the lack of historical data on products, but also by the degree of product innovation and change. Delphi is applicable when dealing with uncertainty in an area of imperfect knowledge. Test results have shown that Delphi is superior when compared with other group judgment techniques (like conference groups). The Delphi method can be used when the number of participants exceeds the number with which it is possible to conduct meaningful face-to-face discussion. It overcomes problems resulting from time and cost constraints, which may prevent panelists meeting at a single place or time. In addition, the inherent anonymity of the Delphi method allows the participation of competing companies.

Nakatsu and Iacovou (2009) used Delphi method to study the risk factors of outsourcing software development. The authors' first objective was to create empirically generated lists of risk factors both for domestic and offshore outsourcing projects. The second objective was to compare how the risk factors changed and to see which ones were the most important in each project. They conducted three rounds with experienced IT managers from selected organizations. The authors pointed out that the use of the Delphi method provided good commentary and discussion, and identified the most important risk factors, filling a gap in the literature on IT outsourcing. Keil et al. (2013) conducted a study with Delphi that had three phases, in order to identify the skill requirements for project managers in IT projects, as well as to explain the relative importance of these skills. According to the researchers, this was the first study identified that not only used IT project manager skills but also employed a rigorous step-by-step group decision-making approach to rank these skills in order of importance.

A study by Green et al. (2007) found that business was the main application (43%) of the Delphi technique. The authors mention a wide range of Delphi applications, varying from forecasting criminal convictions in a certain place to the number of meals that need to be served at conferences.

Mitchell (1992) recommends the use of the Delphi methodology combined with other forecasting techniques. This combination is justified in cases where the subject matter is of high technical complexity. Webler et al. (1991) presented a variation of the method named Group Delphi, where the feedback process is similar to that conducted in conferences. During the session, the coordinator asked specialists to justify or mention an example of their opinion and panel discussion is encouraged. The main difference compared to the conventional Delphi method is the lack of anonymity. This method can be conducted over one or two days compared to the conventional method, which could take several months.

2.4. Additional tools: decision matrices, interviews and technology prioritization analysis

Mitchell (1992) recommends using the Delphi method combined with other forecasting techniques for the study of subjects with high technological complexity.

Matrices mathematically correlating strategic variables for businesses are used to make business decisions (McNamee and Celona, 2008) and several researchers have combined these tools with qualitative techniques, forecasting decision-making in the development of technological maps (Gerdsri, 2007; Lee et al., 2008; Jin et al., 2015; Yoon and Park, 2007; Yoon et al., 2007).

According to Yin (2010), the interview is a procedure used in social research that aims to collect data or to support the diagnosis or of a social problem. An interview can be: (i) structured, in which there is a previous script that is applied to all the interviewees; (ii) semi-structured, in which there is a script, but the interviewer may introduce new questions throughout the interview process and (iii) unstructured or in depth, in which the interviewer must be highly trained to gather detailed information on a specific topic. Semi-structured and unstructured interviews, focus groups, qualitative examination of texts and other techniques such as conversations and discourse analyzes are typically associated with qualitative research (Brannen, 1992).

Multiple methods approach has been used for many decades as a validation strategy (triangulation 1.0) or to obtain a deeper understanding of the issue (triangulation 2.0) (Flick, 2017). Triangulation 3.0 is proposed by Flick (2017:53-54): "Instead of seeing investigator, theoretical, methodological, and data triangulation as alternative forms, we can integrate them in a more comprehensive way as steps building on each other.". Triangulation can be used to analyze data obtained from different perspectives when elaborating a TRM.

.

3. Methodology

This study proposes a methodology to refine Delphi results as part of the process to design a technology roadmap (TRM), including a decision matrix, interviews with external experts, and a prioritization analysis.

Authors selected action research and a case study approach due to the multitude of intervenient factors and the issue's inherent complexity. The case selected for this research was the use of Delphi to investigate alternative materials for weight reduction, fulfilling imminent OEM's demands (due to emission regulations) at the Brazilian subsidiary of Magneti Marelli COFAP, an Italian auto parts MNC. The case study's data collection combined multiple methods (questionnaires, interviews, and public data), following Eisenhardt (1989) framework.

The team leader in charge of the project at Magneti Marelli is also one of the authors of this research. This greatly facilitated the action research. Technical aspects of the roadmap have been omitted to protect sensitive information; however, it did not had impact on the content of the article once the focus is on the roadmap design process and not on the technical results.

The designer of the action research methodology was Kurt Lewin, who in 1946 developed social work that aimed to integrate ethnic minorities into North American culture. Lewin (1946:202–203) characterized action research as "a comparative research on the conditions and effects of various forms of social action and research leading to social action." This kind of research contributed not only to the generation of scientific knowledge, but also social action. Lewin classified the action research as a cycle of analysis, fact-finding, designing, planning, implementation, and more fact-finding and evaluation. A spiral of several other cycles occurs after this cycle. Susman and Evered (1978) view the action research as a cyclical process with five phases: diagnosing, action planning, action taking, evaluating, and specifying learning. This framework was applied during the course of this article.

Diagnosing is the identification of the organizational problem in a holistic fashion (Baskerville and Wood-Harper, 1996). This action research was conducted along with a technology forecast project aimed to reduce the weight of structural shock absorbers.

A timeline for the action research was set and all data (meeting minutes, reports, analysis) were registered in an "on-board diary".

"Action taking" phase implemented the action plan. The study started with the identification of guidelines for the elaboration of the company's TRM. The next phase was the employment of the morphological analysis combined with Delphi technique, based on the application of multiple-cycle questionnaires for anonymous panelists and convergence towards consensus (Wright and Giovinazzo, 2000).

Morphological analysis was used to decompose the system under study in its subsystems, identifying the basic structure of its building blocks and technologies and restructuring the system in terms of dimensions and values (Wissema, 1976; Zwicky, 1969). These combinations of dimensions and values were used to outline a robust questionnaire, applied in the Delphi research.

The Delphi survey was conducted in two cycles. The questionnaire was first submitted to 58 panelists from the company (product engineers, sales team, process specialists, and procurement and quality team members), as well as third party (external consultants and academics specialized in the product). In the first cycle, the frequency response was 67%. The questionnaire was revised and reevaluated based on trend analysis. The second phase of the research was then conducted using the Survey Monkey software, submitting the issues to the panelists who had responded to the first round. The second cycle's frequency response was 64%.

Next phase of this action research was the "results evaluation". The outcome of the Delphi survey was sent to panelists. The working group then analyzed the frequency of results of the Delphi survey and prepared a prioritization of alternative materials to each basic component of the structural shock absorber.

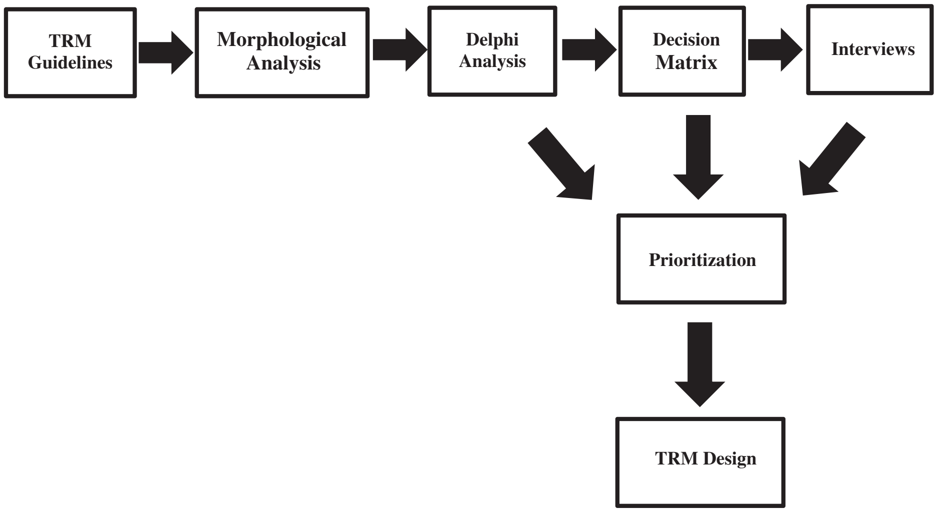

Fig. 1. TRM design framework.

The complementary task was the development of a decision matrix with the purpose of integrating the Delphi results with the technical and commercial guidelines in order to design the technology roadmap. The decision matrix aimed to analyze additional strategic and economic variables. This procedure refined the analysis, enabled a more accurate construction of the technology roadmap, and was a result of the so-called "specifying learning activity" of the action research process that is usually an on-going process (Baskerville and Wood-Harper, 1996).

Triangulation occurred throughout the TRM elaboration process as a result of the action research cycle. The results of the Delphi analysis were compared with results from material R & D projects, as well as with strategic priorities in marketing plan. The final triangulation performed in the last step led to a comparison of Delphi results, the decision matrix output, as well as data collected on interviews with customers, suppliers, and academic experts. This comparative analysis allowed company engineers to prioritize technological alternatives for TRM development.

The proposed TRM design framework is presented in Fig. 1. Table 1 details the proposed objective and methodology for each TRM stage and presents the methodology actually used in the shock absorber case study.

4. Magneti Marelli COFAP

Magneti Marelli is an Italian auto parts company controlled by the Fiat group and consists of eight business units, namely, automotive lighting, motor components, electronics, suspension systems, exhaust, plastic components, and modules, replacement (aftermarket), and motorsport. It is currently one of the global leaders in the development and production of high technology systems and components in the automotive industry.

Magneti Marelli COFAP (MM COFAP) was created in 1997 through the acquisition of the Shock Absorbers Division of Companhia Fabricadora de Peças, COFAP, a Brazilian transnational company founded in 1951 that already operated in this segment. The company has production units in Brazil, United States, Poland, India, and China.

Table 1
TRM process.

Technology roadmap stage	Objective	Methodology	Shock absorber case study
1. TRM guidelines	Identify aspects of company strategy that need to be addressed by TRM	Document analysis, such as company and technology strategic plans	Documents analyzed: strategic technology plans, benchmark analysis, and SWOT analysis
2. Morphological analysis	To decompose a complex system into subsystems and recombine them for all the possible alternatives	Decompose the system in subsystems identifying product and technologies morphologies and restructuring the system in dimensions and values	Shock absorber decomposed in 6 subsystems Function identification Brainstorming for alternative materials
3. Delphi analysis	Obtain a consensus with a group of specialists about future technological trends	Survey using a questionnaire in multiple cycles	39 panelists from company different areas and expertise Two cycles with interactive questionnaire Frequency responses of 67% and 64% Frequency analysis for technology prioritization
4. Decision matrix	Study complementary strategic, economic and sustainability variables alongside purely technical ones in the Delphi study	Matrix to facilitate the interface between the Delphi results and TRM Weighted scores for each alternative prioritization through focus group	Focus group with 7 company specialists that work as product and material engineers
5. Interview with external specialists	Resolve arising conflicts in the analysis of the Delphi results and prioritization of material alternatives	Interviews with external specialists	Semi structured interviews conducted with 4 customers, 3 suppliers and 2 university specialists
6. Technology prioritization analysis	Prioritization of technologies	Triangulation of data sources Table comparing Delphi, decision matrix, and specialists interview results	Prioritization of alternative materials for weight reduction
7. TRM design	Show technology trends	Prioritize technology alternatives	Time allocation of alternative materials in TRM (15 years)

In addition to the production facilities, MM COFAP has development centers in Brazil (São Paulo) and Italy (Turin), and application centers in Michigan (USA), with all the necessary resources for the development and testing of products, from computerized systems design and testing equipment to mobile units, whose purpose is to assemble and test samples in vehicles at customer test sites. The Shock Absorber Technical Center employs about 200 people, of whom 80% are in Brazil and report to the Engineering Director in Italy.

MM COFAP is a market leader in Brazil with approximately 60% of the OEM market and is the sixth largest shock absorber manufacturer in the world, producing 30 million shock absorbers per year. The main product lines manufactured by the company are structural shock absorbers, conventional double- and mono-tube shock absorbers, suspension modules, gas springs, electronic shock absorbers, electronic damping control systems and height leveling systems for vehicles.

An important motivation for this development was the Brazilian government's INOVAR AUTO incentive act, aimed to leverage the competitiveness of the domestic automotive industry. This government initiative mobilized the engineering structures of automakers established in Brazil to form alliances with suppliers and academia aiming technological innovation. One of the main lines of research is the weight reduction of manufactured components in order to meet energy efficiency targets.

All Magneti Marelli business units in Brazil considered INOVAR AUTO's requirements to define their technology strategies. MM COFAP top management priority was to reduce the weight of components, without increase costs. This was the workgroup's primary goal, and for that they should follow the basic guidelines of a technology roadmap framework from Clark and Wheelwright (1993): sustainability, company's image as an innovator for the customer, financial aspects (raw material costs, development expenses, production line equipment costs), and OEM's final costs. Sustainability was also considered as a guideline in TRM development, as per Porter and Kramer (2006).

5. Methodology application for developing the roadmap

The proposed steps to design the roadmap (presented in Fig. 1) will be applied next for reducing shock absorber weight case study.

5.1. Guidelines used for the development of the TRM

The TRM developed by Motorola was used as a reference for this research. This framework correlates the product and technologies necessary to technological develop without losing sight of the fact that these technologies should be aligned with company strategies. Therefore, the guidelines should align the various development prospects of structural shock absorbers. The four stages model of Clark and Wheelwright (1993) can support this intent: (i) development of the product concept; (ii) product planning; (iii) product and process engineering; and (iv) production and market launch.

For this analysis, the company working group used, in addition to personal technical knowledge, the company's data that included strategic technology plans, benchmarking analysis of competitor products, S.W.O.T. analysis, and expert consulting reports. At the end of the review process, the following guidelines were devised:

(i) timeframe for the alternative raw material to be available on the market;
(ii) timeframe for the implementation of the alternative raw material in production;
(iii) increase in cost due to the use of alternative raw material in relation to that normally used in production;
(iv) development costs for the use of alternative raw material;
(v) acquisition and construction costs of equipment for the production of shock absorber components with the alternative raw material;
(vi) construction costs and the purchase of equipment to manufacture components with the alternative raw material;
(vii) reliability of the manufactured product with the use of the alternative raw material;
(viii) potential weight reduction to be obtained with the use of the alternative raw material;
(ix) possibility to recycle the product manufactured with alternative raw material; and.
(x) positive impact on the innovation image of the company with the use of the alternative raw material.

5.2. Morphological analysis of a structural shock absorber

Vehicular shock absorbers aimed at dampening the impact of street and road imperfections on the occupants of the vehicle. These components control the action and reaction of springs through hydraulic pressure in fluids contained in the cylinder, dissipating the stored energy as heat. There are several types of shock absorbers with technical descriptions that are beyond the scope of this project, among them the so-called structural shock absorber, which has a structural function, i.e., it acts as a bearing element of the vehicle's sprung mass, a reason why they are also considered a security feature. The strut is the outer shell of the structural shock absorber, consisting of a reservoir tube, spring seat, lower anchorage, and other external components that are fixed in the reservoir tube, except for the internal components of the shock absorber, such as the rod, pressure tube, and internal valve assembly.

The company's working group, consisting of the main author of this research and five experts in products and the engineering of shock absorber materials, calculated the percentage of weight distribution of the components in relation to the total weight of the shock absorber. Based on this distribution, it was possible to analyze the most critical items to be studied concerning the use of alternative materials and potential weight reduction. Since the structure of the shock absorber consists of about 40 components, the working group divided them into subsets as referred to, namely (see Fig. 2): (i) reservoir tube, (ii) spring seat, (iii) lower mounting assembly, (iv) strut, (v) rod, and (vi) pressure tube. Subsequently, six two-hour brainstorming sessions were held to construct the morphological matrix following the recommendations from Zwicky (1969), enumerating the potential alternative materials. The technological monitoring of competitors and comparison with the current analyzed product were of fundamental importance for a better identification of alternative technologies. This also helped to develop the morphological matrix, which was used as a supporting resource for the Delphi survey (Mitchell, 1992; Yoon and Park, 2007).

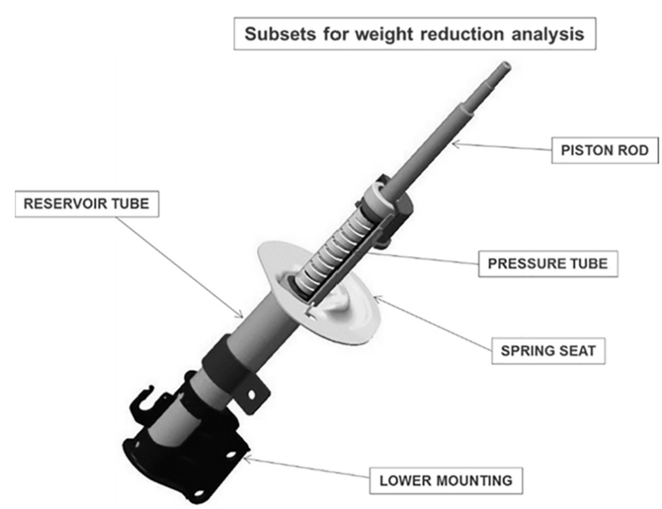

Fig. 2. Structural shock absorber (subsets for weight reduction analysis).
Source: Magneti Marelli Cofap

5.3. Delphi survey

Given the hierarchical level and technical knowledge diversity of the panelists, the use of the Delphi method was appropriate as it preserved anonymity and avoided bias related to conflicts of hierarchy.

After the morphological analysis, the questionnaire was prepared and deployed on two cycles of Delphi survey. After the first cycle, the working group improved the questionnaire based on feedback of participants.

Linstone and Turoff (2011) state that "Delphi is a method for structuring a group communication process, not a method aimed to produce consensus". In other words, participants are lured into thinking about the subject and to give their opinions. Based on this thought, the panelists were asked to justify their answers and give additional comment. This procedure allowed the collection of a large number of opinions and ideas. The same authors recommend the use of multiple perspectives to avoid responses being purely technical.

The first phase of the Delphi survey was conducted with a sample population of 58 panelists, using a questionnaire with 20 questions (Turoff, 1970; Wright and Giovinazzo, 2000). The advantage of conducting the research within the company's internal environment relates to the level of respondent knowledge on the characteristics of the product and its manufacturing process, which allowed a broad set of comments and ideas from the panelists.

The strategy adopted by the coordinator of the study was to sensitize the company's senior management by requesting directors of various departments to encourage employees to complete the Delphi survey. There were two follow-ups over a period of 15 days. After this period, the first phase of the Delphi was closed. The frequency of responses was 67% (39 panelists), which is considered to be quite satisfactory compared to the data reported in literature (e.g. Turoff, 1970; Wright and Giovinazzo, 2000). The issues on which there was not consensus were reviewed and only submitted to the professionals who had responded in the first phase. SurveyMonkey software was used to streamline and facilitate the questionnaire response process. There were two follow-ups over a three-week period after which the survey was closed. The second round showed a return of 64%, which was considered satisfactory. According to Wright and Giovinazzo (2000), abstention of an acceptable range for the second phase of the survey would be 20% to 30%. De Loë et al. (2016:82) analyzed 63 articles about the Delphi technique and concluded that "completion rates, for the first round, should be high in Delphi policy studies because panelists tend to be recruited purposefully".

To simplify the analysis, researchers considered all panelists' answers having the same weight, regardless of their degree of knowledge on the subject matter. This is a facilitator and, at the same time, a limiting factor. The final report was disclosed to all panelists, to company's senior management (one month after the second round of the Delphi survey), and to those who had not responded to the first phase.

The panelists were presented with alternative materials for each component of the shock absorber: reservoir tube, spring seat, lower bracket assembly, piston rod, and pressure tube. Then, they were asked to choose the most appropriate material for each component. The working group then analyzed the frequency of results for the second round of the Delphi survey and prepared a proposal for the prioritization of alternative materials relevant to each component of the structural shock absorber. Fig. 3 shows the response frequencies obtained. For each component, the solid line represents the materials with the highest frequency in the survey. The dotted line represented the materials with the second highest frequency, and the dotted-and-dashed line the third largest frequency. Just to exemplify this procedure, consider the alternatives for piston rod weight reduction; 72% of the panelists chose tubular piston rods as the most feasible solution, followed by machined aluminum (18%), and machined high alloy steel (5%).

Frequency analysis was used to identify alternative materials that would reduce the weight of components of structural shock absorber. The plotting of the results of this graphical analysis in the morphological matrix (see Fig. 3) allowed the researchers to identify possible alternative material combinations. This facilitated the triangulation of the results with those obtained through other methods, such as the decision matrix and interviews with customers, suppliers, and experts, as we shall see in the following topics.

5.4. Decision matrix

The MM COFAP Technology Roadmap Process combined the use of a morphological matrix with Delphi in order to define alternative materials for weight reduction in a specific product. Both techniques were employed using an analysis process based on the opinion of experts, prioritizing alternatives for new technological development.

The use of morphological analysis combined with Delphi allowed the deconstruction of a complex product component and the listing of alternative construction materials. It transpires that the Delphi survey results reflected the traditional technical view of a group of experts formed mostly from the engineering areas. Linstone and Turoff (2011) emphasize the value of introducing multiple analysis perspectives, adding an organizational and strategic perspective to the technical one. This statement is in line with the main feature of the TRM, namely the integration of perspectives from all areas of the company to build strategies, objectives, and actions that the company must take to achieve its goals (Phaal and Probert, 2009).

As was shown in the first stage of the roadmap design process, ten guidelines were set in line with the company's strategy. The working group assigned a weight to each material and guideline (ranging from 1, *not relevant*, to 5, *extremely relevant*), according to its strategic importance to the business. One of the guidelines had a weight varying from 1 to 4. The following scores were given from 1 to 5 for each of the materials, considering each guideline. The sum of these weighted scores resulted in a total weighted score for each specific material. The higher the score, the higher the strategic feasibility of the alternative. Exhibit 1 shows the analysis for a specific component called the buffer reservoir tube (outer tube). Taking the alternate material "high alloy steel with reduction in thickness" as an example, the total weighted score is 112, while the composite material score is 68 (see Fig. 4).

The decision matrix was applied to the other specific components in the morphological analysis. There are a limited number of studies combining the opinions of experts with analytical methods to predict the impact of technologies in corporate strategies (Gerdsri, 2007), highlighting the importance of this methodology for literature.

The working group conducted a comparative analysis (triangulation) of the Delphi results that reflected internal technical views of the company's Shock Absorber Division and the results of the decision matrix. Fig. 5 shows the comparative analysis of several proposals listed in the morphological matrix. The results of the analysis of statistical frequency of the Delphi research results were compared with decision matrix scores. Captions in the left column show the comparison criteria. For example, curve A1 illustrates the results of technological alternatives (materials) that obtained the highest weighted score in the decision matrix analysis compared to those shown in curve B1, which represents the results of technological alternatives (materials) that received the highest response frequency in the Delphi survey. This comparative test was used to score the remaining levels and frequencies (A2 versus B2, B3 versus A3 curves). Curve B4 shows an analysis of alternative materials that was done by the group of experts involved in the development of the decision matrix and was not compared with the Delphi results for the simple reason that the materials used in this analysis were not considered as alternatives for weight reduction by the team that participated in the Delphi survey. One possible explanation for this trend is that these solutions are disruptive and for that reason, not the focus of analysis by the group involved in the Delphi survey.

It is noted, observing the profiles of curves A1 and B1, that a convergence of results was obtained using the two methods, while for other

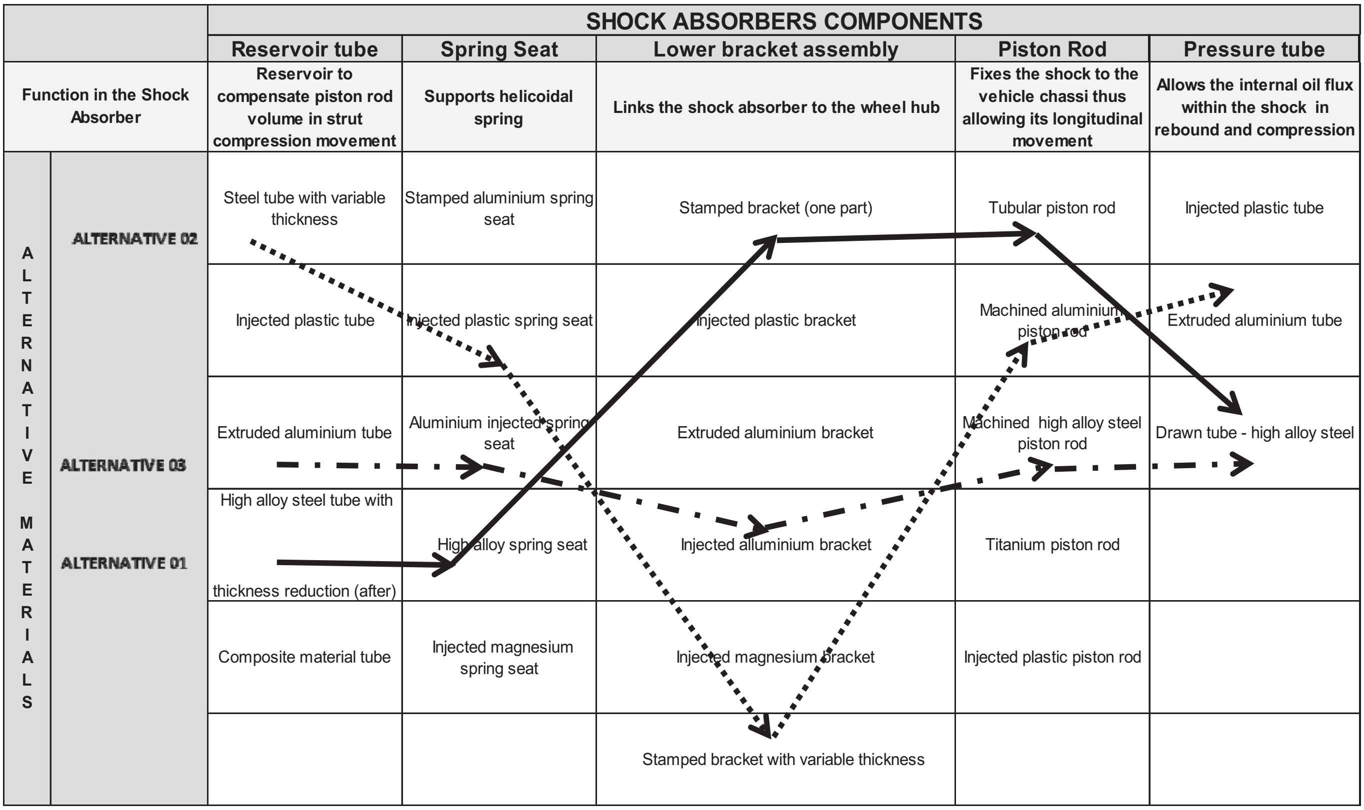

Fig. 3. Morphological matrix showing technological alternatives based on the Delphi survey.

curves convergence was not observed. Analyzing the example of the piston rod, a comparative analysis of curves A1 and B1 shows that the most viable alternative material to replace the material currently used in the production of this (solid steel) component is a tubular steel frame. However, differences were observed in the comparative analysis of curves A2 and B2 (machined high alloy steel versus machined aluminum) and curves A3 and B3 (solid titanium rod versus machined high alloy steel rod). One possible explanation for these differences would be that the Delphi survey results essentially reflect the technical view of the internal technical community, while those obtained through the decision matrix consider the impact of strategic variables of the business.

The combined use of various technological analysis tools (Delphi method, decision matrix) and the graphical representation of the results of these analyzes corroborate the statements of Phaal and Probert (2009) on building a TRM in order to present a holistic view of the business with the participation of major internal stakeholders. The authors of this study go further, triangulating the comparative results of the Delphi analysis X Decision Matrix in relation to those obtained in interviews with customers, suppliers, and academic experts on materials, which reflect the external view of the market, and will be shown in the following sections of this study.

5.5. Interviews, prioritization, and TRM design

The next step involved conducting interviews with four OEM customer experts, three suppliers of raw materials, and two university professors with extensive experience in materials. The "guidelines" in the Decision Matrix were also used for the development of the questionnaire. The results of the interviews were triangulated with those obtained in the Delphi analysis and Decision Matrix, which aimed to prioritize alternative technologies in the construction of the TRM and to validate the survey data (Creswell, 2003). Company documents were also taken into account, such as strategic plan for technology, marketing plan, engineering processes, previous technical development projects, SWOT analysis, and consulting reports.

The results of the triangulation for a specific component of the structural shock absorber (the reservoir tube) are shown in Fig. 6.

To define the first priority, both the Delphi analysis and the decision matrix showed that the use of high steel alloy with reduced thickness is the most viable alternative in terms of implementation in the short term, since it is already available on the market. In the analysis of interviews with customers, suppliers, and experts, both the alternative of high alloy steel with reduced thickness and high alloy steel with variable thickness were given the same level of priority. The decision to prioritize the high alloy steel with reduced thickness first was due to the score obtained through the experts' analysis (112 points) compared to that obtained for steel with variable thickness (102 points). In the TRM, both solutions were classified as being the most appropriate in the short term. This methodology was used for the classification of other priorities.

The product planning model proposed by Phaal et al. (2004) was used for the construction of the TRM. Fig. 7 illustrates the TRM for the reservoir tube, showing the estimated timeframe for the availability of each material. For each proposed technology, the barriers and/or technological resources necessary for industrial scale production of each alternative material (balloons) were also studied.

The method was replicated for the other components of the shock absorber: spring seat, the lower bracket assembly, piston rod, and pressure tube. Then, a complete TRM was designed for all shock absorber components, allowing the interfaces between them to be analyzed. The last line of the TRM for tube reservoir (Fig. 7) shows the potential reduction in weight of the shock absorber as a whole, aggregating the TRMs of the other components.

Emphasis should be given to the decision matrix, which used "guidelines" that considered the following strategic variables: the market, product, technology, manufacturing, sustainability, and the company's innovation image.

Alternative Materialsfor Reservoir Tube		*High Alloy Steel*		*Extruded*		*Injected Plastic*		*Variable*		*Composite*	
Guidelines to design the Technology Roadmap	**Weight**	Grade	Weighted grades	Grade	Weighted grades	Grade	Weighted grades	Grade	Weighted grades	Grade	Weighted grades
Technology availability (ranging from grade 1 = not available in the market to grade 5 = fully available in the market)	4	5	20	3	12	2	8	4	16	1	4
Time for technology implementation in production (aftertechnology's availability) - this guideline is not in Delphi questionnaire:1 to 5 years	1	5	5	5	5	3	3	5	5	1	1
Raw material's cost increment related to current product costs (not in questionnaire). Ranges from 1 (high cost increment) to 5 (low cost increment)	2	4	8	2	4	2	4	3	6	1	2
Development Costs for the technology (not in the questionnaire) ranges from 1 (high cost increment) to 5 (low cost increment)	1	5	5	3	3	2	2	4	4	1	1
Hard Tooling construction costs (not in the questionnaire) ranges from 1 (high cost increment) to 5 (low cost increment)	3	5	15	3	9	2	6	4	12	1	3
Manufacturing equipment costs (not in the questionnaire) ranges from 1 (high cost increment) to 5 (low cost increment)	3	4	12	2	6	2	6	3	9	1	3
Product reliability (1=low to 5 = high) - not in the questionnaire	5	5	25	4	20	3	15	5	25	3	15
% of Weight reduction potential 1 = up to 10%; 2= between 10% and 20%; 3= between 20% and 30%; 4= more than 30%	4	2	8	4	16	4	16	2	8	5	20
Reciclability (not in the questionnaire)1= low reciclability to 5= high reciclability	2	4	8	3	6	2	4	4	8	2	4
Positive impact on Company's Image as Innovator (not in thequestionnaire). 5= high impact to 1= low impact	3	2	6	4	12	4	12	3	9	5	15
Total Weighted Grades			**112**		**93**		**76**		**102**		**68**

Fig. 4. Decision matrix for reservoir tube focusing on high alloy steel technologies.

6. Discussions

Based on the results of action research phases evaluating and specifying learning (Susman and Evered, 1978), the hits and misses of each TRM method is presented below (Table 2).

The study confirmed the need to integrate technical and business views during TRM process. The design of a decision matrix earlier in the process would allow team members to consider strategic business

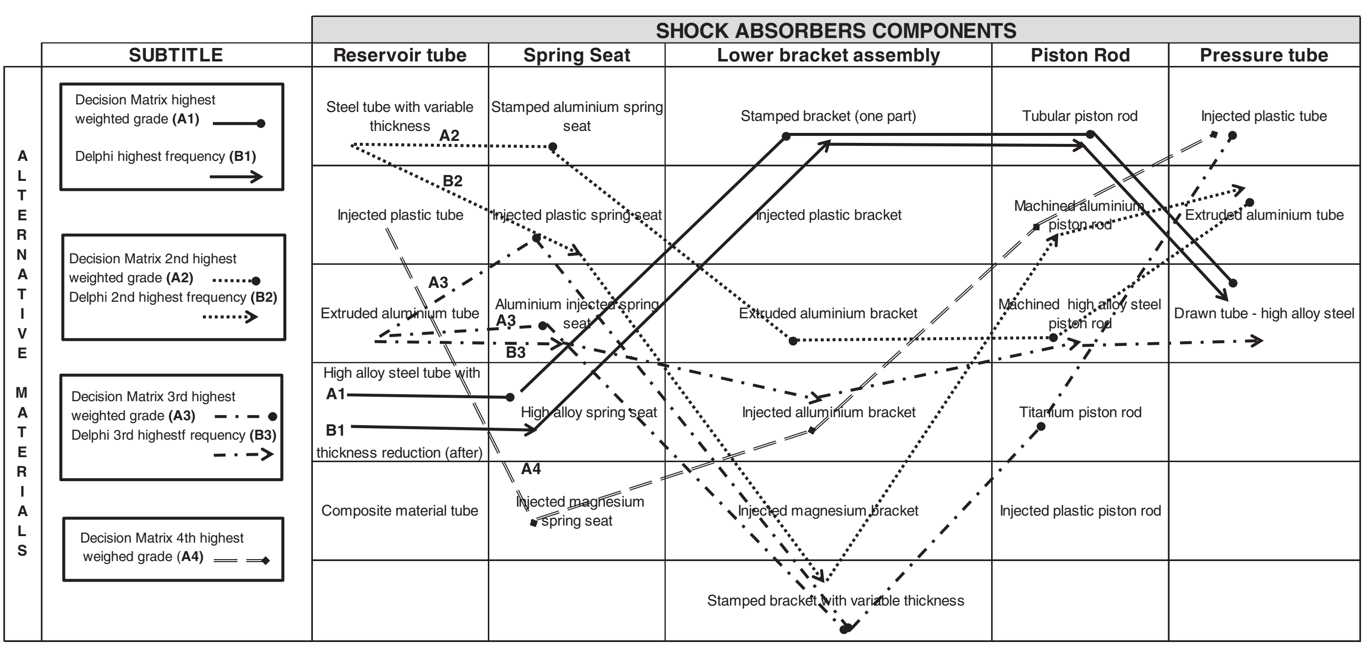

Fig. 5. Comparative analysis of technology using Delphi method and decision matrix with specialists.

Component	TECHNOLOGY PRIORITIZATION	1st PRIORITY
Reservoir Tube	DELPHI	High Alloy Steel with thickness reduction
	Decision Matrix/ranking	High Alloy Steel with thickness red. (112)
	Interviews	High Alloy Steel with thickness reduction Steel with variable thickness
	ROADMAP	**High Alloy Steel with thickness reduction**
	TECHNOLOGY PRIORITIZATION	**2nd PRIORITY**
	DELPHI	Steel with variable thickness
	Decision Matrix/ranking	Steel with variable thickness (102)
	Interviews	High Alloy Steel with thickness reduction Steel with variable thickness
	ROADMAP	**Steel with variable thickness**
	TECHNOLOGY PRIORITIZATION	**3rd PRIORITY**
	DELPHI	Extruded Alluminium
	Decision Matrix/ranking	Extruded Alluminium (93)
	Interviews	Extruded Alluminium
	ROADMAP	**Extruded Alluminium**
	TECHNOLOGY PRIORITIZATION	**4th PRIORITY**
	DELPHI	Not applied
	Decision Matrix/ranking	Injected Plastic (76)
	Interviews	Injected Plastic
	ROADMAP	**Injected Plastic**
	TECHNOLOGY PRIORITIZATION	**5th PRIORITY**
	DELPHI	N/A
	Decision Matrix/ranking	Composite (68)
	Interviews	Composite
	ROADMAP	**Composite**

Fig. 6. Prioritization of technologies (alternative materials) for TRM elaboration.

variables in morphological analysis and Delphi survey. Another suggestion to address this need is to compose a project team including other company departments, such as commercial, with top management support.

There were also lessons learned regarding the Delphi survey:

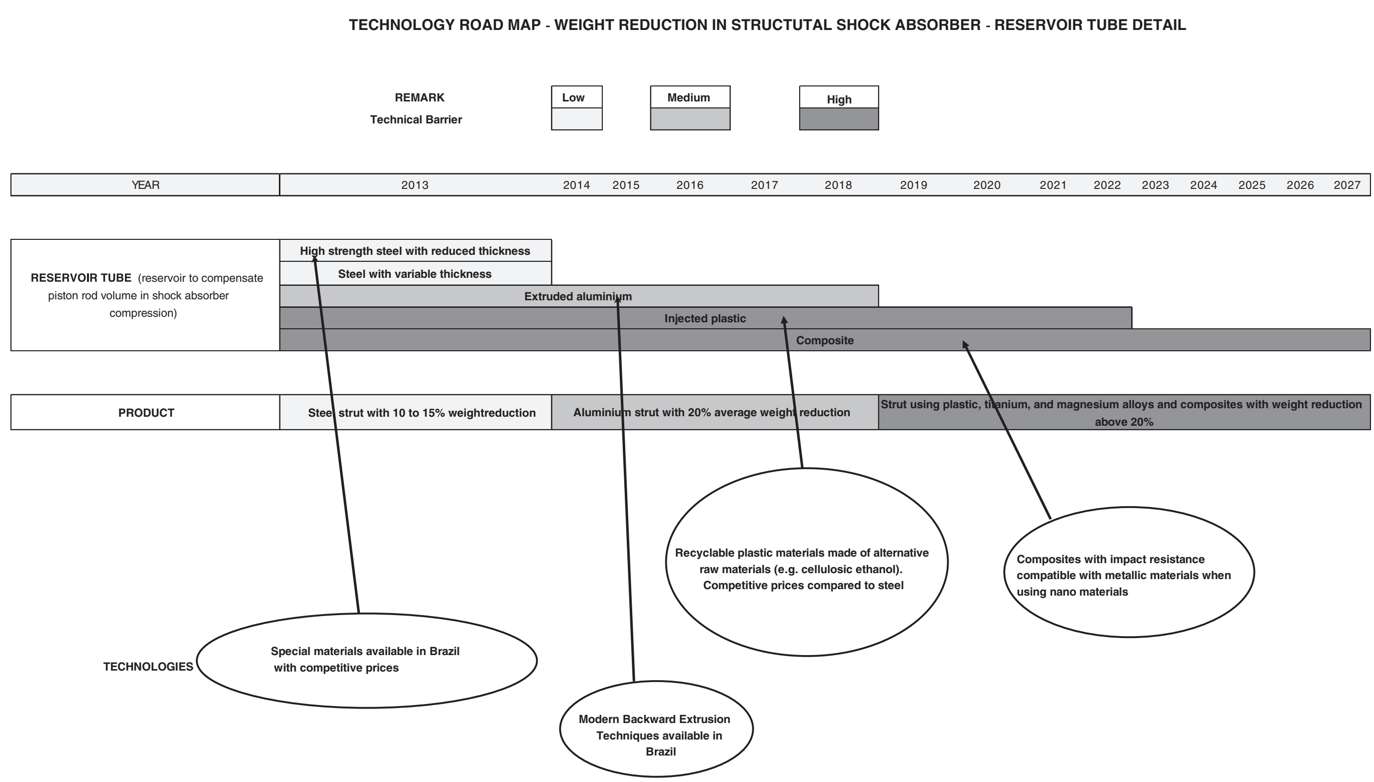

Fig. 7. TRM for tube reservoir.

Table 2
Lessons learned by technology roadmap (TRM) methods.

TRM methods	Hits	Misses
Morphological analysis	• Selection of a team with high qualifications regarding shock absorbers project and production. • Use of Pareto analysis to identify critical components to weight reduction. • Use of brainstorming sessions to construct the morphological matrix. • Clear way to explain structural shock absorber. • Definition of research variable to Delphi survey.	• Lack of team members from commercial department. • Lack of team members specialized in light weight alternative materials (suppliers and university professors). • Technical bias resulting from a team formed only by MM Cofap engineers. • Business strategic variables were not considered in the analysis.
Delphi analysis	• Survey sponsorship by top management. • Criteria for panelists selection (internal and external specialists). • Individual follow up to obtain responses (control spreadsheet). • Questionnaire including request to justify answers and include additional comments. • Questionnaire revision after first round based on statistical analysis. • Use of a software (Survey monkey) for second round. • Summary table facilitated the analysis conducted in following stages of TRM.	• Use of essentially technical variables. • Long time between first and second round, due to other work priorities (both rounds took 3 months). • Use of an excel spreadsheet for submitting and filling in the questionnaire first round. • Results of first and second rounds presented to panelists through electronic mail (instead of a meeting). • Working team comprising only professionals from Product Engineering. • The same weight for the answers of all panelists were used, regardless the degree of technical knowledge on the matter at issue. • Lack the use of statistical methods to amplify the option of alternative technologies.
Decision matrix	• Definition of economic and strategic variables relevant for product success. • The variables weight attribution allowed higher precision. • Summary table facilitated comparing with Delphi and interview results. • Fast to develop.	• Top management could be more involved contributing with business holistic view. • Lack of team members from commercial department. • Lack of team members specialized in light weight alternative materials (suppliers and university professors).
Interview with external specialists	• Selection of a leader supplier for each alternative material family (plastic, ferrous metal, and not ferrous metal). • Interview protocol pre-tested with a university professor. • Interviews through conference call reduced costs and schedule. • Clients, suppliers, and specialists interest in the subject due to INOVAR AUTO incentive program. • Summary table facilitated data triangulation. • Contributed with an external view regarding the alternative materials state of the art.	• Limited number of interviews (8) due to logistics and schedule limitations. • Use of conference call can limit the answers detail level. • Quality level of answers was diverse due to respondents knowledge. • Automaker bias in understanding trend of shock absorbers end users.
Technology prioritization analysis and TRM	• Triangulation of data obtained from Delphi, decision matrix and interviews. • The use of graphic analysis to compare results facilitated the alternatives prioritization. • Development of a prioritization table summarizing the analysis results. • Use of roadmap model 'Product' and 'Technology' (Phaal et al., 2004) helped the research focus. • Adoption of a specific architecture (assembled shock absorber) to roadmap design simplified the work. • Technical barriers classification regarding the use of alternative material in terms of feasibility and competitive cost (compared to currently materials).	• Roadmap designed only by product engineers due to lack of time and involvement of other departments. • Lack of a sense of urgency due to company work routine. • Lack of criteria to evaluate uncertainty level of technological alternative.

- weights should be assigned to the panelists in terms of knowledge, academic training and experience;
- the use of combinatorial analysis can amplify the option of alternative technologies;
- bibliographical research can be used to define a criteria to evaluate the uncertainty level of technological alternative used;
- the utilization of value analysis techniques facilitates the financial analyzes of the each technological alternative;

Authors suggest the comparison of the "Plan T" method (as per Phaal et al., 2004) and with the method used in this research. Finally, during the stage of interviewing external specialists, interviews with final users should also be considered.

7. Conclusions

This paper proposes a methodology to refine Delphi results as part of the process to design a technology roadmap (TRM). The major contribution is a framework to integrate TRM with management techniques, morphological analysis and Delphi survey. The design and application of the decision matrix, interviews, and prioritization with the Delphi results contributed to fill a gap in the literature. The action research suggested that each step of the process had to be planned (considering inputs from literature), and the results registered in an organized way, contributing to the quality of the final product. Fig. 5, which compared Delphi survey responses with the decision matrix, as well as Fig. 6, which prioritized materials for reducing weight, were key to the design of the TRM. These features also constitute a contribution of this study.

The action research methodology contributed to academia as well as the achievement of organization outcomes. The amount of time spent by the researcher, the time spent by the R & D team on this project during eight months, and the access to all the data and other confidential information at MM COFAP were vital in their contribution to the literature. Rarely do university researchers have the opportunity to conduct a study involving such human resources of a company. In addition, access to company networks (customers, suppliers, and university experts) was an additional facilitator.

Regarding the outcomes to the organization, documentation of the whole process contributed to the creation of a competence in the firm about the Delphi methodology. The action research method requires maintenance throughout the whole process, with periodic records of events and decisions that are useful for learning. Many notes were made showing arrangements to be repeated and errors to be corrected in other applications. Today the company not only has a roadmap, but also a template design process that can be used for other products. The literature review was important in the design of a comprehensive Delphi process, and the technique was adapted to the reality of the firm. The knowledge acquired through the application of the method proved to be valuable to the enrichment of the innovation management process at MM COFAP. Technological barriers to the development of the alternative materials were included in the roadmap, generating R & D projects for the company's portfolio. The design of the technological roadmap applied to a specific Magneti Marelli COFAP product using different forecasting methodologies like the Delphi method and decision matrix was extremely challenging and rewarding, since such work had never been done within the company, contributing to strengthen a culture that supports innovation.

It should be stressed that, although the case method does not permit the generalization of conclusions, the results obtained with the application of the proposed methodology indicates a potential contribution to TRM process.

Future studies applying the methodology to other types of products and using quantitative methods are crucial to the development of more effective techniques for technology roadmap elaboration. Subsequently, the possibility of adjusting the method to services should also be explored.

References

Albright, R.E., Kappel, T.A., 2003. Roadmapping in the corporation. Res. Technol. Manag. 46 (2), 27–59. Retrieved from. http://www.ingentaconnect.com/content/routledg/rtm/2003/00000046/00000002/art00006.

Baskerville, R.L., Wood-Harper, A.T., 1996. A critical perspective on action research as a method for information systems research. J. Inf. Technol. 11 (3), 235–246. http://dx.doi.org/10.1080/026839696345289.

Brannen, J., 1992. Mixing Methods: Qualitative and Quantitative Research. Avebury, Aldershot, UK.

Carvalho, M.M., Fleury, A., Lopes, A.P., 2013. An overview of the literature on technology roadmapping (TRM): contributions and trends. Technol. Forecast. Soc. Chang. 80 (7), 1418–1437. http://dx.doi.org/10.1016/j.techfore.2012.11.008.

Clark, K.B., Wheelwright, S.C., 1993. Managing New Product and Process Development: Text and Cases. Free Press, New York.

Coates, V., Farooque, M., Klavans, R., Lapid, K., Linstone, H.A., Pistorius, C., Porter, A.L., 2001. On the future of technological forecasting. Technol. Forecast. Soc. Chang. 67 (1), 1–17. http://dx.doi.org/10.1016/S0040-1625(00)00122-0.

Creswell, J.W., 2003. Research Design: Qualitative, Quantitative, and Mixed Methods Approaches. Sage Publications, Thousand Oaks.

De Loë, R.C., Melnychuk, N., Murray, D., Plummer, R., 2016. Advancing the state of policy Delphi practice: a systematic review evaluating methodological evolution, innovation, and opportunities. Technol. Forecast. Soc. Chang. 104, 78–88. http://dx.doi.org/10.1016/j.techfore.2015.12.009.

Dissel, M.C., Phaal, R., Farrukh, C.J., Probert, D.R., 2009. Value Roadmapping. Res. Technol. Manag. 52 (6), 45–53. Retrieved from. http://www.ingentaconnect.com/content/routledg/rtm/2009/00000052/00000006/art00009.

Eisenhardt, K.M., 1989. Building theories from case study research. Acad. Manag. Rev. 14 (4), 532–550. http://dx.doi.org/10.5465/AMR.1989.4308385.

Farrukh, C., Fraser, P., Hadjidakis, D., Phaal, R., Probert, D., Tainsh, D., 2004. Developing an integrated technology management process. Res. Technol. Manag. 47 (4), 39–46. Retrieved from. http://www.ingentaconnect.com/content/routledg/rtm/2004/00000047/00000004/art00008.

Fenwick, D., Daim, T.U., Gerdsri, N., 2009. Value driven technology road mapping (VTRM) process integrating decision making and marketing tools: case of internet security technologies. Technol. Forecast. Soc. Chang. 76 (8), 1055–1077. http://dx.doi.org/10.1016/j.techfore.2009.04.005.

Flick, U., 2017. Mantras and myths: the disenchantment of mixed-methods research and revisiting triangulation as a perspective. Qual. Inq. 23 (1), 46–57. http://dx.doi.org/10.1177/1077800416655827.

Freeman, C., 1982. The Economics of Industrial Innovation, 3rd ed. Pinter, England.

Galvin, R., 1998. Science roadmaps. Science 280 (5365), 803. http://dx.doi.org/10.1126/science.280.5365.803a.

Gerdsri, N., 2007. An analytical approach to building a technology development envelope (TDE) for roadmapping of emerging technologies. Int. J. Innov. Technol. Manag. 4 (2), 121–135. http://dx.doi.org/10.1142/S0219877007001004.

Godet, M., 2000. Manual de Prospectiva Estratégica. CEPES - Centro de Estudos de Prospectiva e Estratégia, Lisboa, Portugal Retrieved from. http://www.institutobrasilrural.org.br/download/20080615095245.pdf.

Green, K., Armstrong, J., Graefe, A., 2007. Methods to elicit forecasts from groups: Delphi and prediction markets compared. Foresight 8, 17–20. Retrieved from. http://econpapers.repec.org/RePEc:for:ijafaa:y:2007:i:8:p:17-20.

Grisham, T., 2009. The Delphi technique: a method for testing complex and multifaceted topics. Int. J. Manag. Proj. Bus. 2 (1), 112–130. http://dx.doi.org/10.1108/17538370910930545.

Groenveld, P., 2007. Roadmapping integrates business and technology. Res. Technol. Manag. 50 (6), 49–58. Retrieved from. http://www.ingentaconnect.com/content/routledg/rtm/2007/00000050/00000006/art00007.

Jin, G., Jeong, Y., Yoon, B., 2015. Technology-driven roadmaps for identifying new product/market opportunities: use of text mining and quality function deployment. Adv. Eng. Inform. 29, 126–138. http://dx.doi.org/10.1016/j.aei.2014.11.001.

Keil, M., Lee, H.K., Deng, T., 2013. Understanding the most critical skills for managing IT projects: a Delphi study of IT project managers. Inf. Manag. 50 (7), 398–414. http://dx.doi.org/10.1016/j.im.2013.05.005.

Kostoff, R.N., Schaller, R.R., 2001. Science and technology roadmaps. IEEE Trans. Eng. Manag. 48 (2), 132–143. http://dx.doi.org/10.1109/17.922473.

Lee, S., Kang, S., Park, Y., Park, Y., 2007. Technology roadmapping for R & D planning: the case of the Korean parts and materials industry. Technovation 27, 433–445. http://dx.doi.org/10.1016/j.technovation.2007.02.011.

Lee, S., Lee, S., Seol, H., Park, Y., 2008. Using patent information for designing new product and technology: keyword based technology roadmapping. R & D Manag. 38 (2), 169–188. http://dx.doi.org/10.1111/j.1467-9310.2008.00509.x.

Lee, J.H., Phaal, R., Lee, S.-H., 2013. An integrated service-device-technology roadmap for smart city development. Technol. Forecast. Soc. Chang. 80 (2), 286–306. http://dx.doi.org/10.1016/j.techfore.2012.09.020.

Lewin, K., 1946. Action research and minority problems. J. Soc. Issues 2 (4), 34–46. http://dx.doi.org/10.1111/j.1540-4560.1946.tb02295.x.

Linstone, H.A., Turoff, M., 2011. Delphi: a brief look backward and forward. Technol. Forecast. Soc. Chang. 78 (9), 1712–1719. http://dx.doi.org/10.1016/j.techfore.2010.09.011.

McMillan, A., 2003. Roadmapping: agent of change. Res. Technol. Manag. 46 (2), 40–46. Retrieved from. http://www.ingentaconnect.com/content/routledg/rtm/2003/00000046/00000002.

McNamee, P., Celona, J., 2008. Decision Analysis for the Professional. USA, Smart-Org Retrieved from. https://smartorg.com/wp-content/uploads/2011/08/Decision-Analysis-for-the-Professional.pdf.

Mitchell, V.W., 1992. Using Delphi to forecast in new technology industries. Mark. Intell. Plan. 10 (2), 4–9. http://dx.doi.org/10.1108/02634509210012069.

Nakatsu, R.T., Iacovou, C.L., 2009. A comparative study of important risk factors involved in offshore and domestic outsourcing of software development projects: a two-panel Delphi study. Inf. Manag. 46, 57–68. http://dx.doi.org/10.1016/j.im.2008.11.005.

Nidumolu, R., Prahalad, C.K., Rangaswami, M.R., 2009. Why sustainability is now the key driver of innovation. Harv. Bus. Rev. 87 (9), 56–64. Retrieved from. https://hbr.org/2009/09/why-sustainability-is-now-the-key-driver-of-innovation.

Phaal, R., Palmer, P.J., 2010. Technology management: structuring the strategic dialogue. Eng. Manag. J. 22, 64–74. http://dx.doi.org/10.1080/10429247.2010.11431854.

Phaal, R., Probert, D.R., 2009. Technology Roadmapping: Facilitating Collaborative Research Strategy. Institute for Manufacturing, University of Cambridge.

Phaal, R., Farrukh, C.J.P., Mitchell, R., Probert, D.R., 2003. Starting-up roadmapping fast. Res. Technol. Manag. 46 (2), 52–58. Retrieved from. http://www.ingentaconnect.com/content/routledg/rtm/2003/00000046/00000002.

Phaal, R., Farrukh, C.J.P., Probert, D.R., 2004. Technology roadmapping: a planning framework for evolution and revolution. Technol. Forecast. Soc. Chang. 71 (1–2), 5–26. http://dx.doi.org/10.1016/S0040-1625(03)00072-6.

Phaal, R., Farrukh, C.J.P., Probert, D.R., 2006. Technology management tools: concept, development and application. Technovation 26, 336–344. http://dx.doi.org/10.1016/j.technovation.2005.02.001.

Porter, M.E., Kramer, M.R., 2006. Strategy and society: the link between competitive advantage and corporate social responsibility. Harv. Bus. Rev. 84 (12), 78–92. Retrieved from. https://www.ncbi.nlm.nih.gov/pubmed/17183795.

Porter, A.L., Cunningham, S.W., Banks, J., Roper, A.T., Mason, T.W., Rossini, F.A., 1991. Management, technology, and the future. In: Forecasting and Management of Technology, 1st ed. John Wiley & Sons, Hoboken, NJ, pp. 3–16.

Porter, A.L., Cunningham, S.W., Banks, J., Roper, A.T., Mason, T.W., Rossini, F.A., 2011. Forecasting. In: Forecasting and Management of Technology, 2nd ed. John Wiley & Sons, Hoboken, NJ, pp. 65–97.

Probert, D.R., Farrukh, C.J.P., Phaal, R., 2003. Technology roadmapping: developing a practical approach for linking resources to strategic goals. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 217 (9), 1183–1195. http://dx.doi.org/10.1243/095440503322420115.

Skulmoski, G.J., Hartman, F.T., Krahn, J., 2007. The Delphi method for graduate research. J. Inf. Technol. Educ. 6, 1–21. Retrieved from. https://eric.ed.gov/?id=EJ807652.

Stead, J.G., Stead, E., 2000. Eco-enterprise strategy: standing for sustainability. J. Bus. Ethics 24 (4), 313–329. http://dx.doi.org/10.1023/A:1006188725928.

Susman, G.I., Evered, R.D., 1978. An assessment of the scientific merits of action research. Adm. Sci. Q. 23 (4), 582–603. Retrieved from: http://www.jstor.org./stable/2392581.

Turoff, M., 1970. The design of a policy Delphi. Technol. Forecast. Soc. Chang. 2 (2), 149–171. http://dx.doi.org/10.1016/0040-1625(70)90161-7.

Utterback, J.M., 1994. Mastering the Dynamics of Innovation: How Companies Can Seize Opportunities in the Face of Technological Change. Harvard Business School Press, Boston, MA. http://dl.acm.org/citation.cfm?id=189474.

Vasconcellos, E., Wahler, D., Monterossi, J.O., Bruno, M.A.C., 2014. Technological threats and opportunities identification and technological roadmap as tools to improve the portfolio of technological projects. Int. J. Automot. Technol. Manag. 14 (1), 25–45. http://dx.doi.org/10.1504/IJATM.2014.058364.

Webler, T., Levine, D., Rakel, H., Renn, O., 1991. A novel approach to reducing uncertainty: the group Delphi. Technol. Forecast. Soc. Chang. 39 (3), 253–263. http://dx.doi.org/10.1016/0040-1625(91)90040-M.

Wissema, J.G., 1976. Morphological analysis: its application to a company TF investigation. Futures 8 (2), 146–153. http://dx.doi.org/10.1016/0016-3287(76)90064-1.

Wright, J.T.C., Giovinazzo, R.A., 2000. Delphi: uma ferramenta de apoio ao planejamento prospectivo. Caderno Pesquisas Administr. 1 (12), 54–65. Retrieved from. https://pt.scribd.com/document/257810335.

Yin, R.K., 2010. Case Study Research: Design and Methods. Sage Publications, Thousand Oaks, CA.

Yoon, B., Park, Y., 2007. Development of new technology forecasting algorithm: hybrid approach for morphology analysis and conjoint analysis of patent information. IEEE Trans. Eng. Manag. 54, 588–599. http://dx.doi.org/10.1109/TEM.2007.900796.

Yoon, B., Phaal, R., Probert, D., 2007. Morphology analysis for technology roadmapping: application of text mining. R & D Manag. 38 (1), 51–68. http://dx.doi.org/10.1111/j.1467-9310.2007.00493.x.

Zwicky, F., 1969. Discovery, Invention, Research Through the Morphological Analysis. Macmillan, Ontario, Canada.

Luiz A. Bloem da Silveira Junior holds a bachelor's degree in Metallurgical Engineering from the University of São Paulo – USP; an MBA degree in Knowledge, Technology, and Innovation from FIA; an MSc in Business Administration from the USP; and is a PhD student in Business Administration at the same university. He has experience as a manager in steel plants, automotive, and auto part MNCs in quality, product engineering, and R & D. He is a consultant specializing in innovation management and professor in post-graduation courses in engineering schools. His areas of research include innovation management, technology forecasting and management, strategic alliances, and PLM.

Eduardo Vasconcellos holds a bachelor's degree in Business Administration from the University of São Paulo – USP; an MBA from Vanderbilt University; and a PhD from the USP. He is a full professor at the School of Economics, Management, and Accounting from the USP. His areas of research and consulting are technology management and organization design for innovation. He is a member of the advisory board of IAMOT – International Association for the Management of Technology and Member of the Advisory Board of GLORAD – Global Research and Development Organization. He has more than one hundred publications. He was also a visiting scholar at Northwestern University and Carleton University.

Luis Fernando A. Guedes has over 20 years of executive experience in multinational companies and ten years as a professor of management, MBA, and post-MBA courses at FIA. He is a professional speaker and an expert consultant in innovation management. He holds a PhD in Business Administration from the School of Economics, Management, and Accounting of the University of São Paulo – FEA/USP; a master's in Business Administration from EAESP/FGV; an MBA in International Management from FIA; and an MBA in Telecommunications from FEI, where he graduated in Computer Engineering.

Liliana Vasconcellos Guedes is a professor at the School of Economics, Management, and Accounting from the University of São Paulo – FEA/USP and Coordinator of the Design Lab at FEA/USP. She holds a PhD, master's, and bachelor's degree in Business Administration from FEA/USP. She was a visiting scholar at Linköping University, Sweden, and the University of Illinois at Urbana-Champaign (USA).

Renato Machado Costa holds a bachelor's degree in Mechanical Engineering from the USP, an MSc and PhD degrees in Business Administration at the same university. He has experience in manufacturing companies as well as in corporate software, IT services, and consulting. He is a professor of post-graduation courses of Management, Business, and IT. His areas of research include innovation management, international business, strategic alliances, business models, and servitization.